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COMPRESSIVE PROPERTIES OF A CLOSED-CELL ALUMINUM FOAM AS A FUNCTION OF STRAIN-RATE AND TEMPERATURE.

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The compressive deformation behavior of a closed-cell Aluminum foam (ALPORAS) manufactured by Shinko Wire. Co. in Japan was evaluated under static and dynamic loading conditions as a function of temperature. High strain rate tests (1000 - 2000/s) were conducted using a split-Hopkinson pressure bar(SHPB). Quasi-static and intermediate strain rate tests were conducted on a hydraulic load frame. Little change in the flow stress behavior as a function of strain rate was measured. The deformation behavior of the Al-foam was however found to be strongly temperature dependent under both quasi-static and dynamic loading. Localized deformation and stress state instability during testing of metal foams will be discussed in detail since the behavior over the entire range of strain rates indicates non-uniform deformation.

INTRODUCTION

The high-strain-rate stress-strain response of metallic foams has received increased interest in recent years related to their light-weight and the potential for large energy absorption during deformation. Understanding the deformation mechanisms present in these materials will enable designers to more fully utilize their energy absorbing characteristics. Previous studies of fully-dense annealed Al alloys have shown that temperature more strongly affects the yield and flow stress behavior than strain rate[1].

A number of previous studies have probed the constitutive response of Aluminum based foams at room temperature[2-10]. The compressive response of a variety of Al-based foams at low strain rates[2-5] and the high-strain-rate work of Dannemann [6], Deshpande[7]. Mukai[8], Hall[9], and Paul[10] has shown that: a) the initial elastic modulus of Al-foams is generally lower than a fully-dense alloy, b) imperfections in the cell walls [11] lead to localized deformation, stress concentrations around the deformed regions, and due to this a decreased modulus, c) the Al-foam exhibits yield behavior when the local distortions link to form a deformation band, and d) subsequent oscillations in the stress-strain curves of Al-foams tested in compression are associated with additional deformation band collapse.

Although these conclusions are common to the findings of most previous investigators, there remain many differences in interpretation concerning the strain-rate sensitivity of Al-alloy foams. There is evidence that the stress-strain behavior of the closed cell Al-foam (Alporas) of this study exhibits some strain-rate sensitivity[6,8]. However, other studies have shown that there is no strain-rate sensitivity in other metal foams [7, 9]. Geometry effects may for example limit the strain rate sensitivity in low relative density foams. However, there has been to date no evidence linking strain-rate sensitivity to processing or structure although the retention to cold-work in manufacturing metal foams appears likely. Scatter in the overall stress-strain behavior and the low yield and flow stress in Al-foams makes it difficult to quantify the magnitude of the strain-rate sensitivity if any exists.

Sample-size and lubrication effects are also critical to the quantification of the mechanical response of metal foams due to the cell size, cell wall thickness, and the speed of sound through these structures. The speed of sound in the structures, which is linked to the stress state stability, seems to vary with the wall geometry.

The objective of this paper is to present results illustrating the effect of systematic variations of strain rate and temperature on the constitutive response of the Alporas closed cell Al foam.

EXPERIMENTAL TECHNIQUES

This investigation was performed on a commercial closed cell-aluminum alloy foam with the trade name ALPORAS (Shinko Wire Co.)[12]. The chemical composition of the foam is Al-1.42Ca-1.42Ti-0.28Fe-0.007Mg (by weight %) with an approximate relative density of 0.08 (density of foam divided by the density of the parent material). The average cell diameter is reported to be ~3mm [12] with a cell wall thickness of ~85µm.

Cylindrical compression samples 18.4mm in diameter by 9.5mm in length (high rate tests) and 25.3mm in diameter by 28.0mm in length (low rate tests) were electro-discharge machined from the as-received foam material. Compression tests were conducted at strain rates of 0.001 and 1.0 s^{-1} at 93K, 173K, 295K in laboratory air using an MTS 880 hydraulic load frame. Dynamic tests were conducted at strain rates from ~1000 to 2000 s^{-1}, and temperatures of 93K, 173K, and 295K, utilizing a split-Hopkinson pressure bar (SHPB) equipped with 23mm diameter AZ31B magnesium pressure bars. Mg bars were utilized because they yield a higher signal-to-noise level compared to the maraging steel bars traditionally utilized for many Hopkinson-Bar studies[13]. Strain limiting rings were utilized to sequentially control the deformation in each loading of the Al-foam sample. Without the rings the stored energy in the SHPB leads to deformation in the samples well beyond the recording ability of the data acquisition system.

The inherent oscillations in the dynamic stress-strain curves and the lack of stress equilibrium in the specimens during the test make the determination of yield strength inaccurate at high strain rates. Temperature variations for the quasi-static tests were conducted by allowing cooled nitrogen gas to flow through the compression platens. SHPB tests below 295K were achieved using liquid nitrogen to cool the SHPB bars and using conduction to cool the sample. Samples were lubricated using either a thin layer of molybdenum disulfide grease or molybdenum disulfide spray lubricant.

RESULTS AND DISCUSSION

The compressive engineering-stress versus engineering-strain response of the Al-foam was found to be slightly sensitive to the applied strain rate between 0.001 and 2000 s^{-1}. The plateau stresses of were parallel with a small average increase in level for increasing strain rate. The yield strength, flow plateau stress displayed greater dependence on temperature between 93K and 295K. The yield strength of the foam at 295K shown in Fig. 1 increased from ~1.4 MPa at 0.001 s^{-1} to 1.7 MPa at

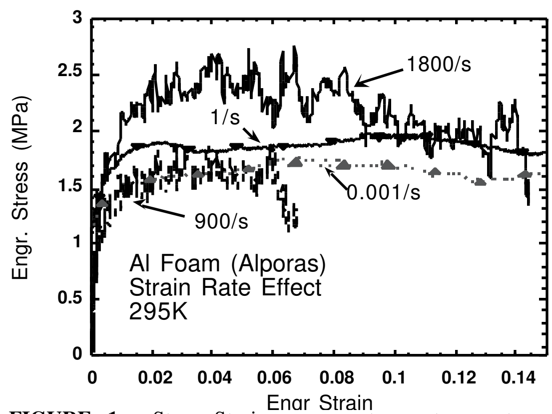

FIGURE 1: Stress-Strain response at room temperature of Alphoras Al foam (relative density = 0.08) as a function of strain rate at 295K. Note: ~2000 s^{-1} is a compendium of many load and reload tests .

1.0 s^{-1} to ~1.9 MPa at a strain rate of 1800 s^{-1}. However, tests above a strain rate of 1700 s^{-1} are complicated by non-uniform attainment of a uniaxial state of stress. The result of the 900 s^{-1} test shows a yield of only ~1.3 Mpa, but it exhibits a more uniform state of stress. These results are consistent with previous strain rate studies on cellular aluminum alloys considering the statistical variation in the material[5-10]. Due to the documented deformation characteristics of these closed-cell foams[10] the data generated from the SHPB studies was flawed based on the requirements for valid uniaxial-stress SHPB experiments[13,14]. A uniform stress state, which is essential for valid SHPB tests, is seen to be problematic at best within this material at strain-rates of 0.001s^{-1} and above due to non uniform deformation of the foam. Nevertheless, the high-rate constitutive response of the foam was carefully quantified to identify the high-rate mechanical response of the foam.

To assure valid high-rate measurements on the Al foam are being measured, it is instructive to examine the different wave analyses[15] used to calculate sample stress from the Hopkinson bar strain as shown in Fig. 2a. In the 1-wave analysis the sample stress is directly proportional to the bar strain measured from the transmitted bar. The 1-wave stress analysis reflects the conditions at the sample-transmitted bar interface and is often referred to as the sample "back stress". This analysis results in smoother stress-strain curves, especially near the yield point. Alternatively in a 2-wave analysis, the sum of the synchronized incident and reflected bar waveforms (which are opposite in sign) is proportional to the sample "front stress" and reflects the conditions at the incident/reflected bar-sample interface.

A valid, uniaxial Hopkinson bar test requires that the stress state throughout the sample achieve equilibrium during the test and this condition can be checked readily by comparing the 1-wave and 2-wave stress-strain response. We know from the observed deformation of the Al-foam samples that the stress state within the samples is not uniform (Fig. 3b). Since the 2-wave stress oscillates about the 1-wave wave stress, as seen in Figure 2a we have some confidence that the forces measured represent the overall "bulk" loads on the Al-foam samples. For the current study on Al foam only tests meeting this criterion of stress-state stability were deemed acceptable. At strain rates of ~1800 s^{-1} the 1-wave and 2-wave signals were found to be divergent at the beginning of each test and the strain rate is seen to be slightly increasing with strain. Although the 2-wave oscillates around the 1-wave curve there is sufficient evidence to therefore question the validity of these results. At higher strain rates the 1-wave and 2-wave signals were found to be divergent for the entire test (invalidating the stress analysis as discussed previously).

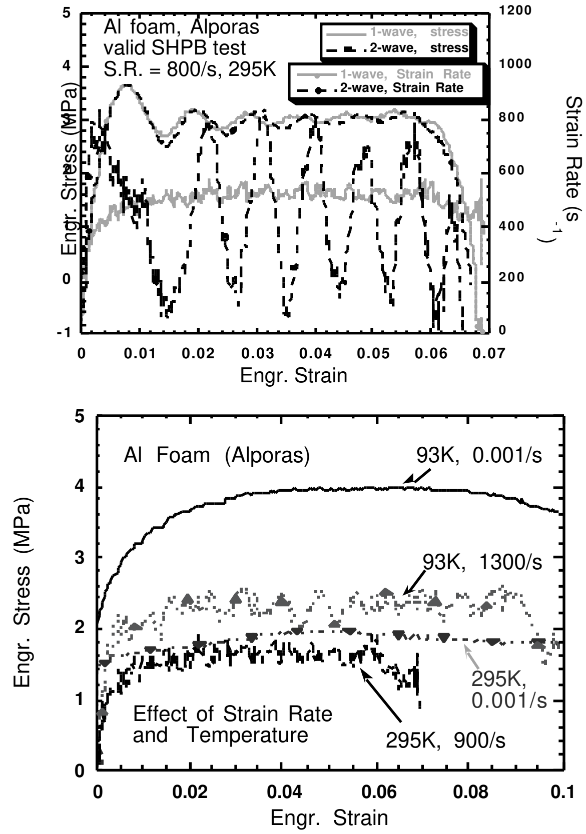

FIGURE 2: Stress-strain response the Al foam, a) showing 1- and 2-wave stress curves in addition to the strain rate; and b) as a function of temperature and strain rate.

The yield strength of the Al foam studied was found to exhibit a reproducible and pronounced dependence on test temperature as seen in Figure 2b, decreasing from ~4.0 MPa at 93K to 1.8 MPa at 295K loaded at high-strain rate. A similar effect of temperature on the stress-strain response of the Al foam was seen during quasi-static testing. This temperature dependency of the Al-foam is thought to reflect the temperature dependence of the pre-existing defect substructure in the foam formed during manufacturing[16].

Finally, the Al foam samples displayed strain-rate sensitivity with respect to densification during testing. Samples loaded at high-rate behaved nearly identical to the low rate tests in terms of the uniformity of the deformation behavior. The primary difference between the two loading-rate responses is seen in the strain at which the buckling bands have saturated and "bulk" densification initializes, where the stress begins to increase after the plateau (at ~ 63% strain in low rate tests and at ~51% for strain rates of 10^3).

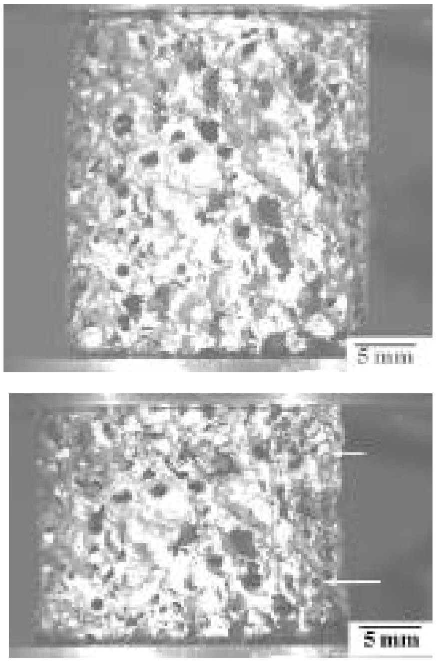

FIGURE 3: optical micrograph of Alporas Al foam: a) as received, and b) after 30% strain. Note the deformation bands indicated by the arrows.

SUMMARY AND CONCLUSIONS

Based upon a study of the influence of strain rate and temperature on the constitutive response of Al foams, the following conclusions can be drawn: 1) the compressive stress-strain response of an Al-foam was found to depend on the applied temperature; 77K to 295K and to a lesser degree on the strain rate; 0.001 to ~2000 s^{-1}, 2) decreasing temperature at 2000 s^{-1} was found to increase the maximum flow stress in Al foam from ~1.4 to 4 MPa, 3) the deformation of the Al foam was found to be heterogeneous in nature, and 4) the Al foam failed at high-strain rate via deformation band collapse.

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